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Time-Lapse Imaging in Polar Environments

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Although the drivers of climate change and its consequences in polar regions are becoming better understood [*Holland and Bitz*, 2003] and well monitored [*Serreze et al.*, 2002; *Doran et al.*, 2002b], measuring the responses of polar landscapes to changing climate boundary conditions is challenging: Polar landscapes typically respond slowly to warming but abruptly to melting [*Gooseff et al.*, 2011].

Time-lapse imaging has emerged as the premier method for capturing evidence of punctuated change to cryosphere landscapes [*Balog*, 2008; *Ahn and Box*, 2010; *Dickson et al.*, 2013; *Levy et al.*, 2013]. In polar environments, time-lapse imaging captures the dynamics of complex processes while also making the consequences of climate change relatable to the public. Here we highlight recent advances in time-lapse imaging for geosciences research in Antarctica.

Existing Monitoring

Most cryosphere landscape monitoring focuses on the collection of long-term climate and surface energy balance measurements [e.g., *Fountain et al.*, 1999; *Brown et al.*, 2000; *Harris et al.*, 2001; *Doran et al.*, 2002a; *Smith et al.*, 2003; *Romanovsky et al.*, 2010; *Guglielmin et al.*, 2012]. These commonly combine mapping, geographic information system analyses, satellite mapping, ground-based imaging, and/or lidar scans [*Barnhart and Crosby*, 2013], but surface climatology data sets typically sample at a rate far in excess of the imaging or mapping rate. Thus, although meteorological data are typically continuous, measurements of landscape response are not. This mismatch motivated the acquisition of time-lapse imaging data sets that could be integrated with continuous meteorology data.

No off-the-shelf time-lapse system on the market permits the collection of time-lapse data with any camera or the integration of that imaging data with any time series data set collected from nearby environmental sensors. Thus, techniques had to be developed to integrate any time series data set, collected on any data logging platform, with any time-lapse imaging data set.

Time-Lapse Imaging Stations

Time-lapse imaging of polar landscapes presents several challenges, primarily low temperatures that inhibit battery performance and rugged terrain that severely limits accessibility to remote stations. These factors amplify the importance of developing an ultrastable imaging system because servicing equipment, particularly at stations that can only be accessed by helicopter, is often logistically impossible.

Commercial cameras can perform time-lapse image acquisition through a modification of their firmware. We have implemented the Canon Hack Development Kit (http://chdk.wikia.com/wiki/CHDK), which was developed by camera users to provide automated time-lapse functionality built into the system firmware. After modifying the firmware on new cameras, we field-installed them and

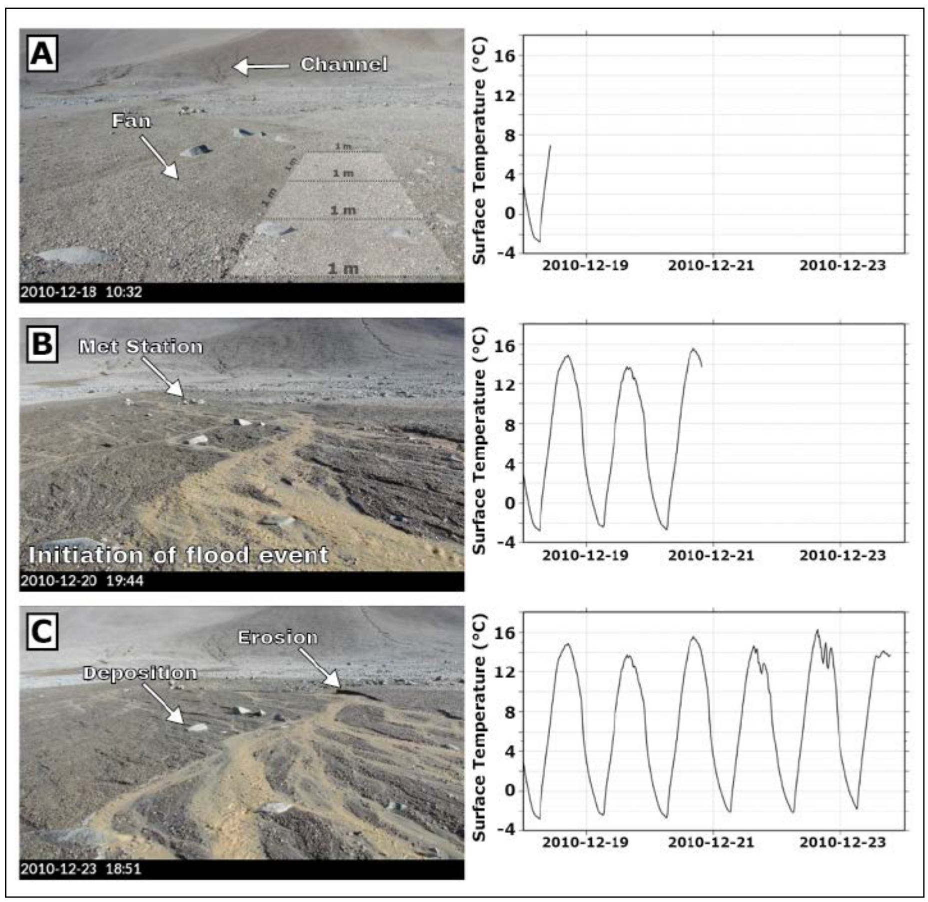

Fig. 1. *Three frames from a time-lapse sequence on the floor of Upper Wright Valley in the McMurdo Dry Valleys showing relationships between surface temperature and gully discharge on daily time scales. Time-lapse imaging captured an anomalous flooding event on a gully fan in December 2010. Surface temperatures were recorded by the meteorological (met) station shown in Figure 1b. The scale displayed in Figure 1a was made from grid measurements performed in the field during data acquisition.*

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recorded images during five field seasons in the McMurdo Dry Valleys (~77°S–78°S, 160°E–140°E).

Low-power (~3-volt) cameras can run through austral summer at 5-minute intervals using two photovoltaic panels (~7.5 watts) that charge two sealed 12-volt gel cell batteries. This power system performs well in extreme cold and is in compliance with environmental protocols governing fieldwork in Antarctica. Cameras operate until late March, providing observations that encompass the entirety of the peak melting season, and continue after science teams must return from the field. These image data (landscape response) are paired with environmental sensor data (climatic forcing), which are collected from stations within the camera's field of view.

All image and sensor data are stored within a Linux file system for which software has been developed to generate side-by-side movies of climate measurements synchronized with time-lapse images (Figure 1) [*Dickson et al.,* 2013; *Levy et al.,* 2013]. A user accessing these data is prompted for key parameters (instrument, duration, interval, frame rate, etc.). The software queries the sensor data for the temporally closest measurement for each image on the basis of the image time stamp and plots the measurement next to the image. Thus, images and meteorology station recordings need not be precisely synchronous, as the software will find the closest possible match. This means that any image source can be paired with any tabular data file even if the two are not designed to be used in concert.

The linked time-lapse image/environmental sensor approach has led to new discoveries and key process associations. Two examples from the McMurdo Dry Valleys stand out—they demonstrate how integrated meteorologic stations and time-lapse data techniques can provide insight into glacial, fluvial, and permafrost processes.

Brine Generation and Transport

The first example is from Don Juan Pond, located in Upper Wright Valley in the McMurdo Dry Valleys. The pond is the most saline natural body of water on Earth [*Meyer et al.,* 1962], composed almost entirely of a calcium chloride brine. As such, it does not fully freeze and is a provocative site for determining the limits of extremophiles on Earth [*Samarkin et al.,* 2010] and the potential for brines and primitive life on Mars [*Burt and Knauth*, 2003; *Marchant and Head*, 2007].

Long hypothesized to be sourced by deep groundwater [*Harris and Cartwright*, 1981], direct observations of inputs into the pond had previously not been published. During the 2009–2010 field campaign, time-lapse imaging provided direct evidence of discharge from seeps within the approximately 20-centimeter soil layer, correlated with daily temperature spikes, with no evidence of a deep groundwater contribution (see Movie 1 in the additional supporting information in the online version of this article) [*Dickson et al.*, 2013].

This shallow brine activity is consistent with brine generation by deliquescence of calcium chloride salts [*Wilson*, 1979], which was also documented as time-lapse sequences recorded soil hydration correlated with increases in relative humidity (Movie 2 in the online version) [*Dickson et al.,* 2013]. Time-lapse imaging in this analysis refined scientific understanding of brine generation and transport in polar environments, providing hypotheses for potential brine activity on Mars [*McEwen et al.*, 2011].

Determining the Causes of Melting of a Buried Ice Sheet

Additionally, time-lapse imaging coupled with in situ meteorological observations in Garwood Valley, Antarctica, was used to determine the causes of accelerated loss of a buried ice sheet remnant emplaced in the valley bottom during the Pleistocene [*Levy et al.*, 2013], about 20–30 thousand years ago. Time-lapse imaging showed that as the formerly buried ice was exposed to intense summer illumination at a dramatic ice cliff, melting and erosion of the frozen landscape accelerated.

While biannual lidar scans revealed that the melting rate of the ground ice was accelerating, the relative roles of melting versus debris avalanching and block failure from exposed ice cliffs were not clearly resolved. Likewise, because the stage of the Garwood River, which flows past the ice cliffs, is highly variable on seasonal and diurnal time scales [*Levy et al.*, 2013], short visits to the field site were not sufficient to determine whether heat transfer from the river to the riverbank ice deposits was a significant factor.

Time-lapse imaging at the site revealed two major insights into the causes of accelerated ground ice melting in Garwood Valley (see Movie 3 in the online version). First, debris avalanches that remove the ice's insulating sediment cover are activated thermally, occurring most often when the top of the underlying ice is already melting. This dusts the exposed ice with warm, dark sediment that further accelerates the melting along the full face of the ice cliffs. In addition, river level, which was thought to be warming the ice and causing melting, is usually well below the level at which ground ice melting and block failure occur in the riverbank, suggesting that insolation processes, rather than fluvial advection of heat, dominate the energy balance leading to rapid erosion of this ancient ice.

The Power of Observing Landscapes as They Evolve

Time-lapse imaging integrated with meteorological measurements provides unprecedented documentation of landscape processes as they evolve with changing climate conditions. The products generated enable fundamental scientific discoveries that are valuable to the scientific community and easily relatable to the public, including policy makers.

This versatility is motivating the development of related techniques, including stereo imaging with digital elevation model generation for three-dimensional time lapse (time-lapse topography), infrared time-lapse imaging for analysis of surface thermal evolution, and satellite communications with time-lapse stations for remote access to data. The value of time-lapse imaging is maximized when it is treated as a component of a larger monitoring network, focused on connecting the response of the Earth's surface to the environmental processes that shape it.

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